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We explore the scenario where the core of a proto-neutron star (with densities above deconfinement value) shrinks into the equilibrated strange matter object. The left-out matter (the envelope of mass $M_{env.}$) free-falls following the core contraction releasing tremendous energies, up to $E_{QN} \simeq 4 \times 10^{52}$ ergs as a result of strangeness contamination or conversion or baryons to quarks − a phenomena we call Quark-Nova. We show that 'dirty' fireballs are a natural outcome of Quark-Novae and could in principle account for Gamma Ray Burst precursor activity. We argue that in general the Quark-Nova ejecta (the 'dirty' fireball) is absorbed or attenuated by the slow preceding Supernova ejecta explaining why only 3% of bursts exhibit precursor activity.

I. INTRODUCTION

Gamma Ray Burst (GRB) precursor activity was defined by Koshut et al. (1995) as any case in which the first episode has a lower peak intensity than that of the remaining GRB emission and is separated from the remaining emission by a background interval that is at least as long as the remaining emission. The precursor episode seems to indicate an impending main episode with peak intensity typically about 10 to 100 times less than that of the remaining GRB emission. The best-documented case is GRB 900126 (Murakami et al. 1991) where clear X-ray emission was exhibited about 10 seconds prior to the onset of the gamma-ray event. It could be modeled by blackbody radiation of temperature $kT = 1.58 \pm 0.26$ keV. Other (less documented and sporadic) cases of bursts with preburst X-ray activity have been suggested (Laros et al. 1984; Murakami et al. 1992; Sazonov et al. 1998). Koshut et al. (1995) estimated that 3% of the GRBs observed with BATSE exhibit precursor activity in the 20 keV band (average). There have been suggestions that the precursor might be an early spectral variation in the main burst (see in't Zand et al 1999 for the case of GRB 980519). However, there is no convincing evidence that the early X-rays originate from a physical process that is similar to that giving rise to the remainder of the burst.

Preburst activity is important in constraining the nature of the central engine of the GRBs (Paczyński 1998, for example). Any 'dirty' fireball model is likely to generate more or less thermal emission from the optically thick, relatively slow ejecta, at the very beginning of the explosion (Dermer et al. 1999; Dermer et al. 2000). In the Quark-Nova model, we show that a 'dirty' fireball is a natural outcome. We start with a proto-neutron star where the core density is assumed to be above deconfinement limit (see Glendenning 1997 for example). In the event that only the core reaches the strange matter saturation density following cooling, it physically separates from the rest of the star and contracts to the stable strange matter object. The fireball is a consequence of the radiation released as a result of the conversion of the infalling envelope material to quarks. The outer envelope material is ejected in the process leading, as we show later, to a 'dirty' fireball.

The letter is presented as follows: in §2 we briefly review the concept of strange matter and the corresponding strange stars. The Quark-Nova phenomena is described in details in §3 where we demonstrate that a 'dirty' fireball is a natural outcome. We conclude in §4.

II. STRANGE MATTER MIXTURE AND STRANGE STARS

Traditionally this mixture is modeled with an equation of state based on the MIT-bag model of quark matter (Farhi & Jaffe, 1984) in which quark confinement is described by an energy term proportional to the volume. This gives a simple equation of state

$$P = a(\rho - \rho_{ss})c^2, \tag{1}$$

where a is a constant of model-dependent value (close to, but generally not equal, to 1/3 of the MIT-bag model).

Different models of the *(u,d,s)* mixture have been suggested. An example of the binding energy vs density of such a system is shown in Figure 1 (Dey et al. 1998). One finds that from about 3 to $7\rho_N$ the *(u,d,s)* mixture has more binding energy than ^{56}Fe. Strange matter saturates around $5\rho_N \equiv \rho_{ss}$ with an energy about 40 MeV per baryon less than ^{56}Fe and is therefore very stable. Dragging a baryon from $\sim \rho_N$ to $\rho_{ss} \sim 5\rho_N$ results on the release of a binding energy (as radiation) of the order of 40 MeV. Because the binding energy is model dependent we define it as a free parameter, $B_{conv.}$., and choose the 10 MeV fiducial value as first defined in Witten (1984).

The possible existence of strange stars (SSs), is a direct consequence of the above described conjecture that strange matter may be the absolute ground state of strong interacting matter rather than ^{56}Fe (Bodmer 1971; Witten 1984; Alcock et al. 1986). Figure 2 shows the SS Mass-Radius plane resulting from the EOS described in Dey et al. (1998). SSs can acquire masses up to $1.44 M_\odot$, with radii up to 7.06 km (for non-rotating stars). However there is no lower limit on their size, and they may be the most compact objects (besides black holes) which exist in the universe.

SSs remained purely theoretical entities. This changed in the last few years, thanks to the large amount of fresh observational data collected by the new generation of X-ray and γ-ray satellites. In fact, recent observations suggest that the compact objects associated with the X-ray pulsars, the X-ray bursters, particularly the SAX J1808.4-3658, are good SS candidates (Li et al. 1999).

III. QUARK-NOVA

SSs may form as compact remnants of massive supernova (the direct process; see Glendenning 1997 for example), or by converting neutron stars into quark stars (Olinto 1987; Cheng & Dai 1996; Bombaci & Datta 2000). In our scenario, only the core is converted to strange matter and contracts to the corresponding stable compact/quark object. This allows for new and richer dynamics.

A. Formation of a bare SS and envelope collapse

Assume a proto-neutron star (PNS, of mass M_{PNS}) is formed with the core density above deconfinement value (a state with the u and d quarks). Conversion of *(u,d)* matter to *(u,d,s)* is a cooling process and takes place via weak interactions where non-leptonic (for example, $u + d \to u + s$) process is of greater rate (Anand et al., 1997). The speed of contamination/conversion is limited by the low weak rate of conversion of d quarks into s quarks and by the rate at which the quarks diffuse. In special circumstances, the conversion time-scale is estimated to be of the order of minutes (Olinto 1987, Heiselberg et al. 1991) and is very sensitive to the temperature and the equation of state. Since the strangeness contamination does not spread in an explosive manner, we obtain the interesting situation where the core density exceeds ρ_{ss} much before the rest of the star. The core immediately shrinks to the corresponding stable bare strange matter object (see Figure 2) and physically separates from the rest of the star. By contracting, it drives the collapse (free-fall) of the left-out matter in a fraction of a millisecond. Note that, if the density of the core does not exceed the (u,d,s) favored density (namely, ρ_{ss}) then it will never undergo transition into the lower energy branch of the matter. The PNS remains a contaminated stable neutron star.

B. Energies

During the process of envelope collapse we shall have tremendous energy release.

1. Gravitational energy

The accretion luminosity (the gravitational potential energy released in the form of radiation during the collapse) is (Frank, King, & Raine 1992),

$$L_{acc.} = 2\eta_{acc.} G M_{ss} \dot{m} / R_{ss} \ . \tag{2}$$

The parameter $\eta_{acc.}$ measures the accretion efficiency and $\dot{m}$ is the accretion rate; since the collapse occurs in a fraction of a millisecond, it is best to think of it as $\dot{m} \simeq M_{env.}/ms$.

The accretion energy is thus,

$$E_{acc.} \simeq \eta_{acc.} M_\odot c^2 \left(\frac{M_{env.}}{M_\odot}\right)\left(\frac{M_{ss}}{M_\odot}\right)\left(\frac{3\ \mathrm{km}}{R_{ss}}\right) \ . \tag{3}$$

2. Conversion energy

Each baryon (the envelope material) converted to strange matter generates a photon of energy $B_{conv.}$ (via, $n \to u + 2d, d + u \to u + s$). The conversion energy is therefore

$$E_{con.} \simeq \frac{M_{env.}}{(m_n - B_{nuc.}/c^2)} B_{conv.}\ \mathrm{MeV}, \tag{4}$$

where m_n is the baryon mass and $B_{nuc.}$ the nuclear binding energy. Equation above is best written as

$$E_{con.} \simeq \eta_{conv.} \left(\frac{M_{env.}}{M_\odot}\right) M_\odot c^2, \tag{5}$$

where $\eta_{conv.} = B_{conv.}/(m_n c^2 - B_{nuc.})$ is the *strangeness conversion efficiency.*

The energy released in the QN is thus

$$E_{QN} = \eta_{QN} M_\odot c^2 \left(\frac{M_{env.}}{M_\odot}\right) \ , \tag{6}$$

where

$$\eta_{QN} = \left(\eta_{acc.}\left(\frac{M_{ss}}{M_\odot}\right)\left(\frac{3\ \mathrm{km}}{R_{ss}}\right) + \eta_{conv.}\right) \ . \tag{7}$$

Only the densest innermost core of the PNS is likely to reach ρ_{ss}. The mass of the tiny contracted core we can write as $M_{ss} \simeq 4\pi/3\rho_{ss}R_{ss}^3$ giving

$$\eta_{QN} = \left(0.016 \times \eta_{acc.}\left(\frac{R_{ss}}{3\ \mathrm{km}}\right)^2\left(\frac{\rho_{ss}}{\rho_N}\right) + \eta_{conv.}\right) \ . \tag{8}$$

A scrutiny of equation above shows that the first term in the RHS can be neglected ($R_{ss} < 1$ km and $\eta_{acc.} \ll 1$ while $\eta_{conv.} \simeq 0.01$). Or,

$$\eta_{QN} \simeq \eta_{conv.} \ , \tag{9}$$

implying,

$$E_{QN} \simeq 2 \times 10^{52}\ \mathrm{ergs}\left(\frac{M_{env.}}{M_\odot}\right)\left(\frac{\eta_{QN}}{0.01}\right) \ , \tag{10}$$

The energy released from the QN can be as high as $\simeq 4 \times 10^{52}$ ergs since $M_{env.,max} = M_{PNS,max} \simeq 2M_\odot$ is to be expected.

C. The 'dirty' fireball and precursor emission

If the radiation energy density aT^4 ($kT = B_{conv.}$) exceeds that of the gravitational energy density in the envelope, energy outflow in the form of ions occurs. One can show that the condition

$$aT^4 > \frac{GM_{ss}}{R_{ss}}\rho_{env.} \ , \tag{11}$$

with ρ_{env} defining the envelope density, is equivalent to

$$\frac{\rho_{env.}}{\rho_N} < 0.06 \times \left(\frac{3\ \mathrm{km}}{R_{ss}}\right)^2\left(\frac{5\ \rho_N}{\rho_{ss}}\right)\left(\frac{B_{conv.}}{10\ \mathrm{MeV}}\right)^4 \ . \tag{12}$$

As expected, the amount of envelope material ejected is very sensitive to $B_{conv.}$. For the fiducial value, $B_{con.} \simeq 10$ MeV, only the outer part of the falling envelope ($\rho_{env.} > 0.06\rho_N$) are ejected. Such a density regime is well described by the equation of state of Baym, Pethick & Sutherland (1971) from which we estimate the amount of mass ejected to be of the order of $M_{ejec.} \simeq 10^{-3}M_\odot$. The initial energy to mass ratio of the fireball is then,

$$\zeta = \frac{E_{QN}}{M_{ejec.}c^2} = 10 \times \left(\frac{\eta_{QN}}{0.01}\right)\left(\frac{M_{env.}}{M_\odot}\right) \ . \tag{13}$$

We estimate

$$1 < \zeta < 20 \ , \tag{14}$$

by recalling that $0.1M_\odot < M_{env.} \simeq M_{PNS} < 2M_\odot$. The minimum stable neutron star is $0.1M_\odot$ (Baym, Pethick, & Sutherland 1971). The range in ζ derived above define the 'dirty' fireball regime. Such fireballs are known to produce transient emissions that are longer lasting and most luminous at X-ray energies and below (Dermer et al. 1999; Dermer et al. 2000), and constitute ideal candidates for GRB precursor.

D. QN-SN interaction and precursor activity

The SN-ejecta (traveling at speeds $\sim 0.1c$) is followed at higher speeds ($\sim 1c$) by the QN-ejecta. A collision between the accelerated baryons and the pre-ejected Newtonian SN ejecta might resemble an external shock (the slow velocity of the outer shell would not be relevant here). However, because the SN-shell contains several solar masses - much more than a typical ISM - such a collision is likely to produce a "non thermal" GRB and precursor activity is cut short by the interaction.

The radial expansion time of the SN-ejecta is related to t_{ss} - the strangeness contamination time- as $R_{SN-shell} = v_{SN-shell} \times t_{ss}$. The total duration time (in the observer frame) of the precursor is thus

$$t_{obs} = \frac{R_{SN-shell}}{2\zeta^2 c} = \frac{t_{ss}}{2000}\left(\frac{10}{\zeta}\right)^2\ \mathrm{s} \ . \tag{15}$$

Since only 3% of GRBs exhibit precursor activity, we argue that in general the QN transition takes place in much less than an hour following the SN collapse. How such a precise timing can be achieved, depends on the intricate physics of the spread of strangeness contamination which is beyond the scope of this paper.

IV. CONCLUSION

At the heart of our model is the strangeness contamination of the core of a PNS born with central densities above deconfinement values. The contaminated core contracts to the corresponding stable quark object. We showed that the resulting QN phenomena leads to a 'dirty' fireball which we suggest as a candidate for GRB precursor. The details of the intricate process of contamination and cooling need to be worked out in order to make our model less speculative.

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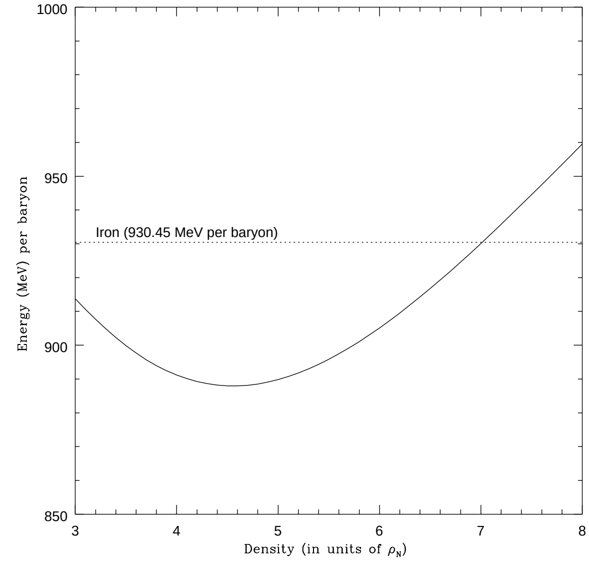

FIG. 1. Energy per baryon for strange quark matter in terms of the density (in units of ρ_N) as modelled by Dey et al. (1998). The horizontal dotted line shows the energy per baryon in ^{56}Fe which is 930.4 MeV. At high density ($\sim 5\rho_N$), strange matter with its lower energy is the preferred state of matter (the difference in this energy between Iron and the strange matter results in excess of the binding energy for the Strange matter vs Iron).

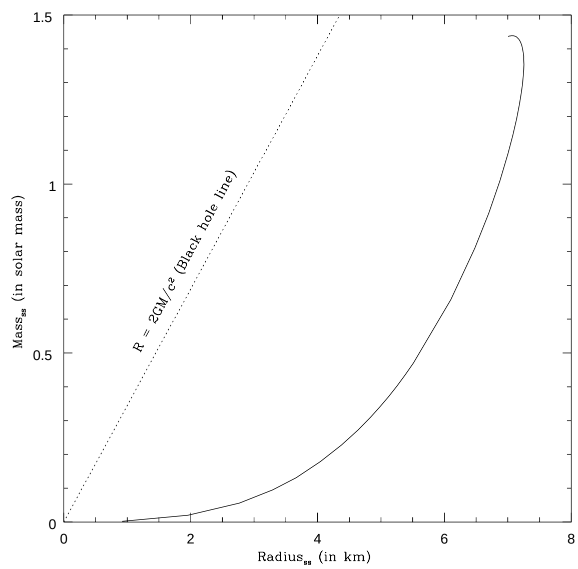

FIG. 2. The Mass-Radius ($M-R$) relation for non-rotating SSs (Dey et al. 1998). The maximum mass is $1.44 M_\odot$ while there is no minimum mass along the sequence. In this model, the radius of a typical SS never exceeds 7.06 km.